

Tunneling competition of photoexcited carriers in a system of monolithically integrated dual multiple InGaAs/AlGaAs and GaAs/AlGaAs quantum wells

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ABSTRACT

Vertical transport of photoexcited carriers has been studied in a p-i-n diode whose intrinsic layer contains two different multiple quantum wells (MQW), GaAs/Al_{0.15}Ga_{0.85}As (MQW1) and strained In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As (MQW2) isolated by a thick Al_{0.15}Ga_{0.85}As barrier. Pseudo-negative photocurrent (PC) peaks are observed at exciton resonance wavelengths of MQW1 located far from the n-electrode under low electric fields, while the normal positive excitonic peaks recover with increasing the electric field. Moreover, the PC intensity of MQW1 as a function of inverse electric field shows linear dependence due to Fowler-Nordheim type tunneling with a slope change. The observed PC intensity crossover is rigorously explained by tunneling probability calculations, because of differences in the thickness and height of the transport limiting tunneling barriers, assuming dominance of electron tunneling transport for the PC responses.

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Recently investigations of the vertical tunneling transport of photogenerated carriers have been receiving much attention in the quantum structure of electro-optical devices which utilize nonlinear electro-optical effects [1-3]. To study these effects, photocurrent (PC) spectroscopy is simple and widely used to extract information about the carrier transport. Since PC spectroscopy involves the transport of photoexcited carriers in addition to photoabsorption, many interesting physical phenomena have emerged in the quantum well systems such as a minimum of PC at a maximum of excitonic resonance absorption peak in the perpendicular [4-6] and parallel [7] transport.

In this paper, we investigate vertical transport characteristics of a new-type quantum structure, named monolithically integrated dual multiple quantum wells (MID-MQW) that contains a pair of different multiple-quantum-wells, GaAs/Al_{0.15}Ga_{0.85}As (MQW1) and In_{0.15}Ga_{0.85}As/ Al_{0.15}Ga_{0.85}As (MQW2), isolated by a thick Al_{0.15}Ga_{0.85}As barrier layer in the intrinsic layer of a p-i-n diode. A MID-MQW structure is unique because photocarriers generated in each layer should experience strongly directional transports preferential to the n- or p-electrode since tunneling probabilities of electrons and holes in each MQW are different and inequivalent with respect to the transport direction. Hence, pseudo-negative PC peaks are observed at the exciton resonance wavelengths of MQW1 under low electric fields. Moreover, careful analysis of the PC intensity of MQW1 as a function of inverse electric field (F^{-1}) shows that the observed linear F^{-1} dependence is due to Fowler-Nordheim type tunneling with a slope change, whose crossover is explained by non-uniform tunneling probability calculations within the intrinsic MID-MQW structure.

Figure 1 shows a schematic diagram of the MID-MQW sample structure which was grown on an n-type GaAs (100) substrate by molecular beam epitaxy (MBE). The intrinsic layer consists of dual multiple quantum wells with different heterostructures, GaAs/Al_{0.15}Ga_{0.85}As ($L_Z=10\text{nm}/L_B=10\text{nm}$, MQW1) and strained In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As ($L_Z=10\text{nm}/L_B=25\text{nm}$, MQW2) which are isolated by a 50 nm Al_{0.15}Ga_{0.85}As layer. In this structure, there are three different types of tunneling barriers, i.e., 10 nm Al_{0.15}Ga_{0.85}As (in MQW1), 25 nm Al_{0.15}Ga_{0.85}As (in MQW2) and 50 nm Al_{0.15}Ga_{0.85}As (between MQW1 and MQW2) layers. Moreover, MQW2 with 20 periods is located near the substrate n-side, while MQW1 with 100 periods is near the p-side and therefore far from the n-side. These MQW1 and MQW2 layers are confined by undoped 0.1 μm Al_{0.15}Ga_{0.85}As layers and further clad by n- and p-type Al_{0.15}Ga_{0.85}As layers to form a p-i-n diode structure. The p-i-n diodes were processed into (400 $\mu\text{m} \times 400 \mu\text{m}$) mesas and gold-ring electrodes as contacts on the p-GaAs cap layer were formed by standard photolithography. PC spectra were measured at 100 - 300 K using a halogen lamp and a monochromator for excitation and a computer-controlled electrometer for dc detection, as a function of bias voltage (V_b) ranging from +0.3 V (forward) to -14.0 V (reverse) which was applied to the diode.

Figures 2 (a) and (b) show PC spectra of the MID-MQW sample as a function of applied bias voltage measured at 300 K and 100 K, respectively. In Fig. 2(a), peaks observed at 1.330 eV (932 nm) and 1.449 eV (856 nm) at -14.0 V are due to excitonic transitions (1e-1h) between first quantized levels in the conduction and valence subbands of MQW2 and MQW1, respectively. The peak of MQW2 shifts to the lower energy side when the electric field is increased (due to the quantum confined Stark

effect: QCSE [8]), while no significant shifts are seen for the peak of MQW1. However, we note that the 1e-1h excitonic transition of MQW1 shows a negative peak under low electric fields. When the electric field is increased, the intensity of the PC signal gradually increases at the position of the initially negative peak. Finally it transforms into the positive peak at -14 V. PC spectra shown in Fig. 2(b) measured at 100 K show similar behaviors, except for the expected energy shift due to the temperature dependence of the GaAs band gap. However, the observed PC dips are significantly enhanced at the exciton peak of MQW1. From a comparison between the PC spectra at 100 K and 300 K, two important points are noticed. The PC dips at 100 K are more clearly appeared at all the measured bias voltages, while the dips at 300 K are persistent up to $V_b = -10.0$ V. Moreover, the PC intensity (especially under the low field condition) becomes smaller when the temperature is decreased to 100 K.

First we will discuss the pseudo-negative PC peaks of MQW1. Since the MQW1 is placed near the p-side, an incident light illuminated from the p-side initially reaches the MQW1 and is absorbed partly in that layer. Thus, the light intensity entering into the MQW2 layer results in decreasing at the resonance wavelength of MQW1. Since the number of quantum wells is large enough in MQW1 (100 periods), the MQW1 layer absorbs most of the incident photons at the resonance wavelength. As a result, the number of photons entering into the MQW2 shows a dip at the MQW1 exciton resonance wavelength. The pseudo-negative PC peaks observed at the MQW1 resonance is then explained by assuming the dominance of electron transport as origins of the PC spectral features [6,9]. When the applied field is weak, only electrons created in the MQW2 layer can contribute to the PC signal, because the

electrons generated in MQW1 can not contribute to the signal by the thick blocking barrier between MQW1 and MQW2. Therefore, the appearance of pseudo-negative PC peaks is explained by shadowing effects on the number of photons absorbed in the MQW2 by the MQW1 layer as discussed above. When the electric field is increased, the photogenerated electrons in MQW1 may also contribute to the PC signals by efficient field-induced tunneling through the thick barrier in addition to the PC contribution from the MQW2 layer. Hence the pseudo-negative PC peaks are converted into the normal positive peaks when the electric field is increased [6]. At 100 K the PC dips due to the heavy- and light-hole excitons are more clearly observed for MQW1. The reduced PC intensity with decreasing the temperature is explained by considering the fact that the photogenerated carriers are easily consumed by the temperature-induced radiative recombinations.

In order to evaluate the carrier transport properties, semi-logarithmic plots of the PC intensity of MQW1 are shown in Fig. 3 as a function of inverse electric field. The results are plotted at 100, 200 and 300 K. It is found that the PC intensity as a function of inverse electric field shows linear dependence due to Fowler-Nordheim type tunneling with a slope change around $1/F = 0.03$ (1/(kV/cm)). To quantitatively analyze the slope change, we have calculated the electron tunneling probability of the three different barriers in this heterostructure. Figure 4 shows calculated results of the electron tunneling probability in a semi-logarithmic plot as a function of inverse electric field. From these results, it is inferred that the electrons generated within the MQW1 layer can efficiently move since the tunneling probability for the barrier in MQW1 is higher. When the electric field is low ($1/F$:large), however, it is difficult for

electrons to tunnel through the thick central barrier because of the extremely low tunneling probability. Consequently, only electrons generated in the MQW2 layer which has a relatively higher tunneling probability can contribute to the PC signal under the low electric field. Hence, the PC intensity measured as a function of $1/F$ reflects the gradual slope of MQW2 tunneling probability. Furthermore, the decrease of the low field PC intensity at lower temperatures can be explained in terms of the efficient radiative recombinations of the photogenerated carriers.

When the electric field is increased, it is found that the tunneling probability of the thick central barrier is drastically increased and exceeds the probability for the MQW2 layer above $1/F = 0.04$ (1/(kV/cm)) in agreement with the observed crossover point. As a result, the electrons created in the MQW1 layer can also contribute to the PC signal above the critical field strength, which is determined by the crossover of the tunneling probability. Therefore, the PC intensity as a function of $1/F$ reflects the steep slope of the tunneling probability of the central thick barrier. Hence, the slope change of the PC intensity against F^{-1} is explained by the tunneling probability calculations of three different types of the tunneling barriers contained in this heterostructure.

In summary, we investigate vertical transport of photocarriers in a new-type quantum structure, named monolithically integrated dual multiple quantum wells. It is found that shadowing effects on the PC spectra lead to the appearance of pseudo-negative exciton resonance peaks under low electric fields. Moreover, the PC intensity at the lowest exciton resonance in MQW1 as a function of inverse electric field shows linear dependence due to Fowler-Nordheim type tunneling with a slope

change. The experimental dependence of the PC intensity crossover is explained by tunneling probability calculations because of differences in the thickness and height of the transport limiting tunneling barriers.

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Figure Captions

- Fig. 1 Schematic sample structure of monolithically integrated dual multiple quantum wells.
- Fig. 2 Photocurrent spectra as a function of applied bias voltage at (a) 300 K and (b) 100 K.
- Fig. 3 Photocurrent (PC) intensity as a function of inverse electric field. PC intensity is evaluated at the 1e-1h exciton resonance wavelength of MQW1.
- Fig. 4 Tunneling probability for three different types of tunneling barriers as a function of inverse electric field.

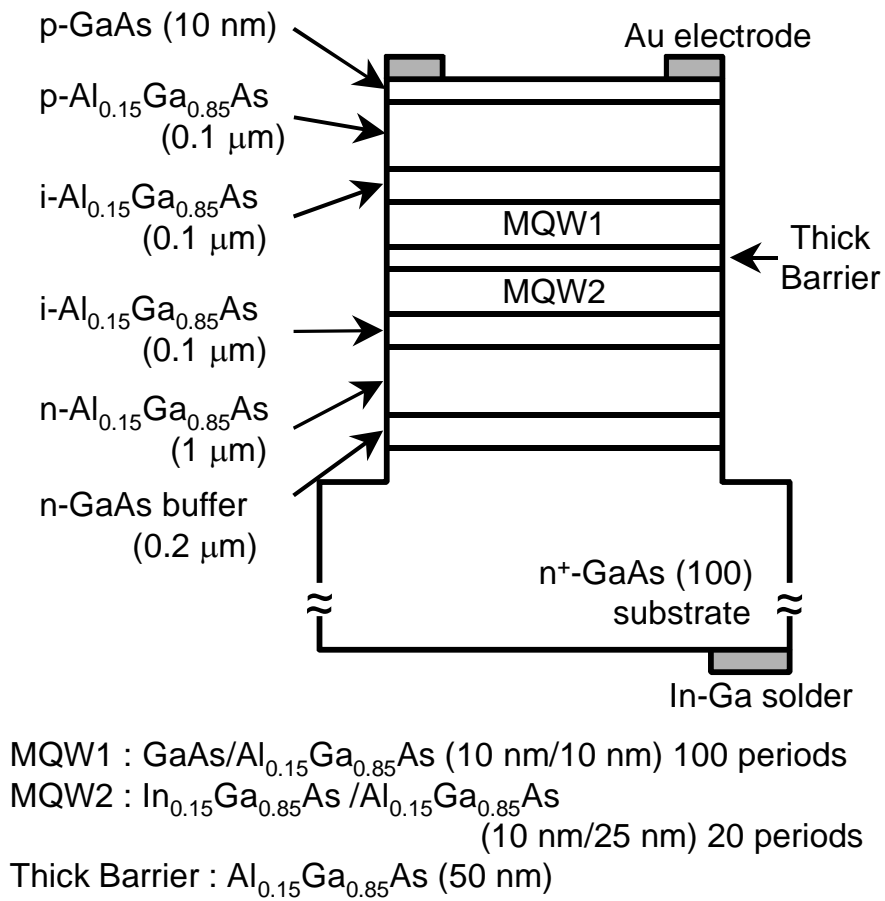


Fig. 1, K. Kawasaki et al., “Tunneling competition of...”

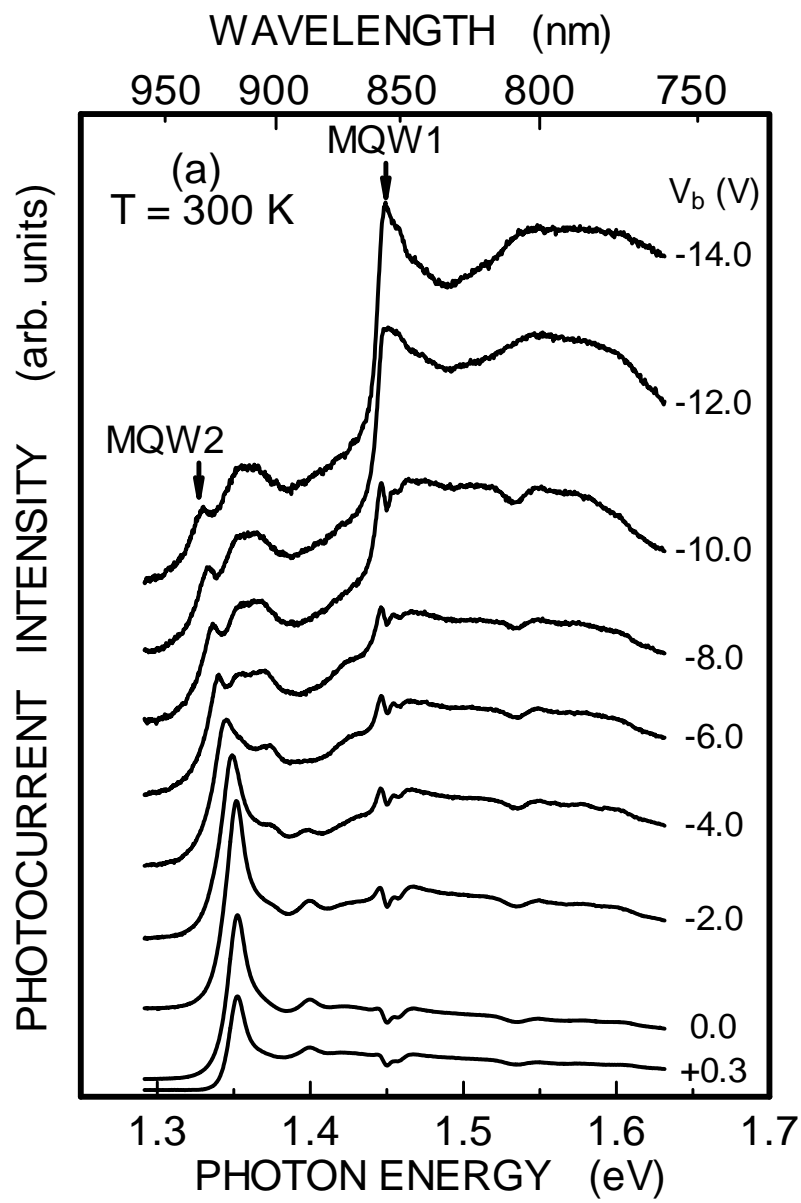


Fig. 2(a), K. Kawasaki et al., "Tunneling competition of..."

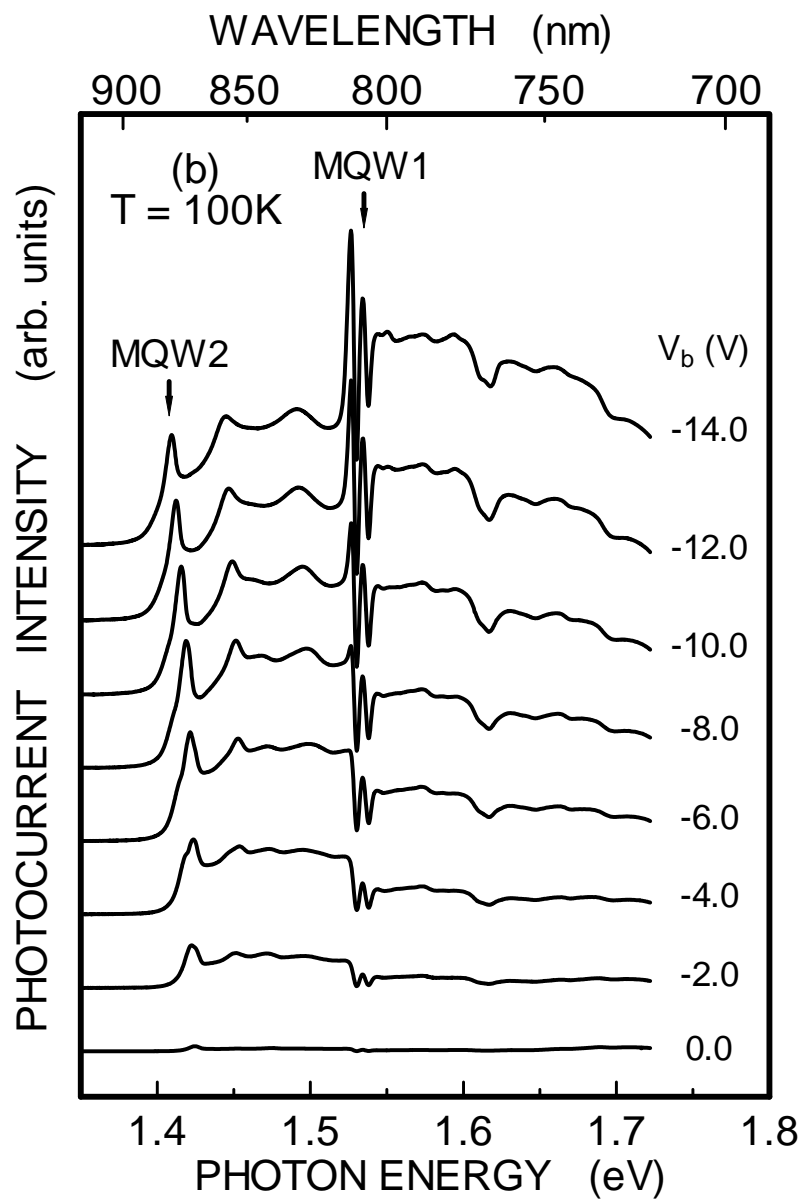


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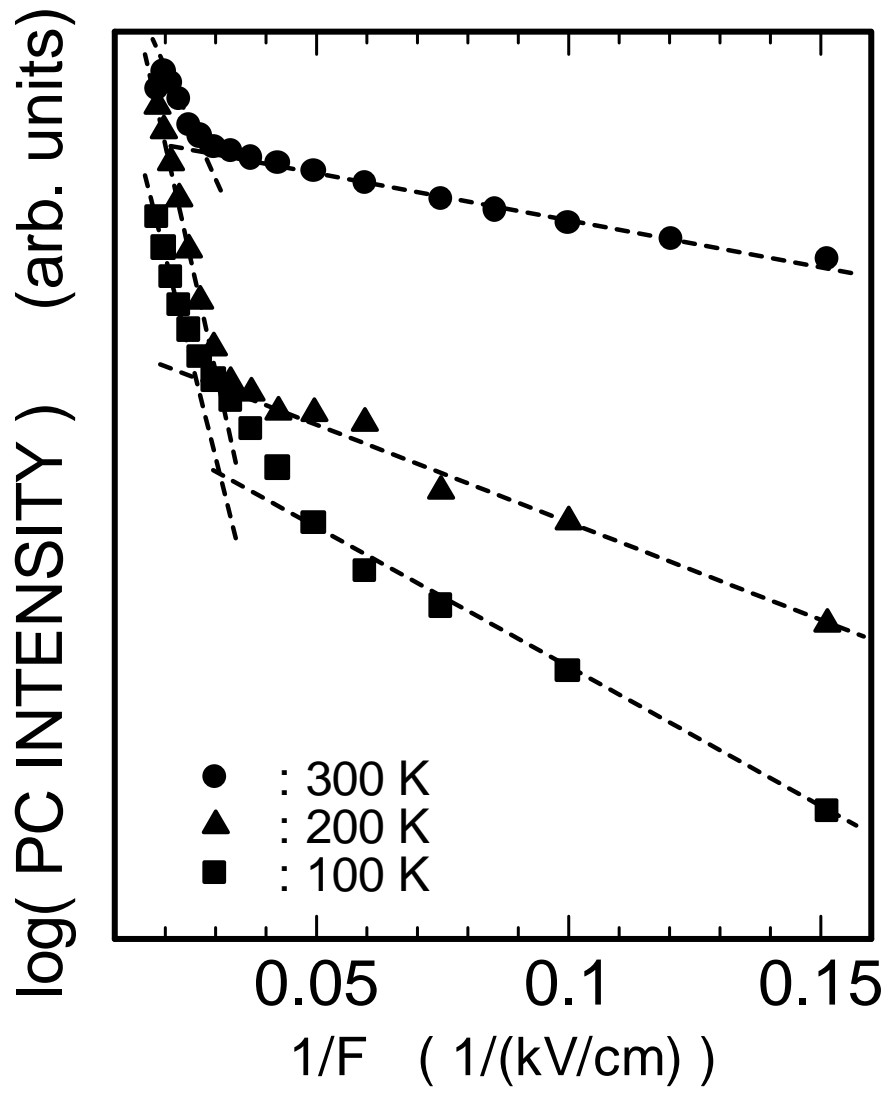


Fig. 3, K. Kawasaki et al., "Tunneling competition of..."

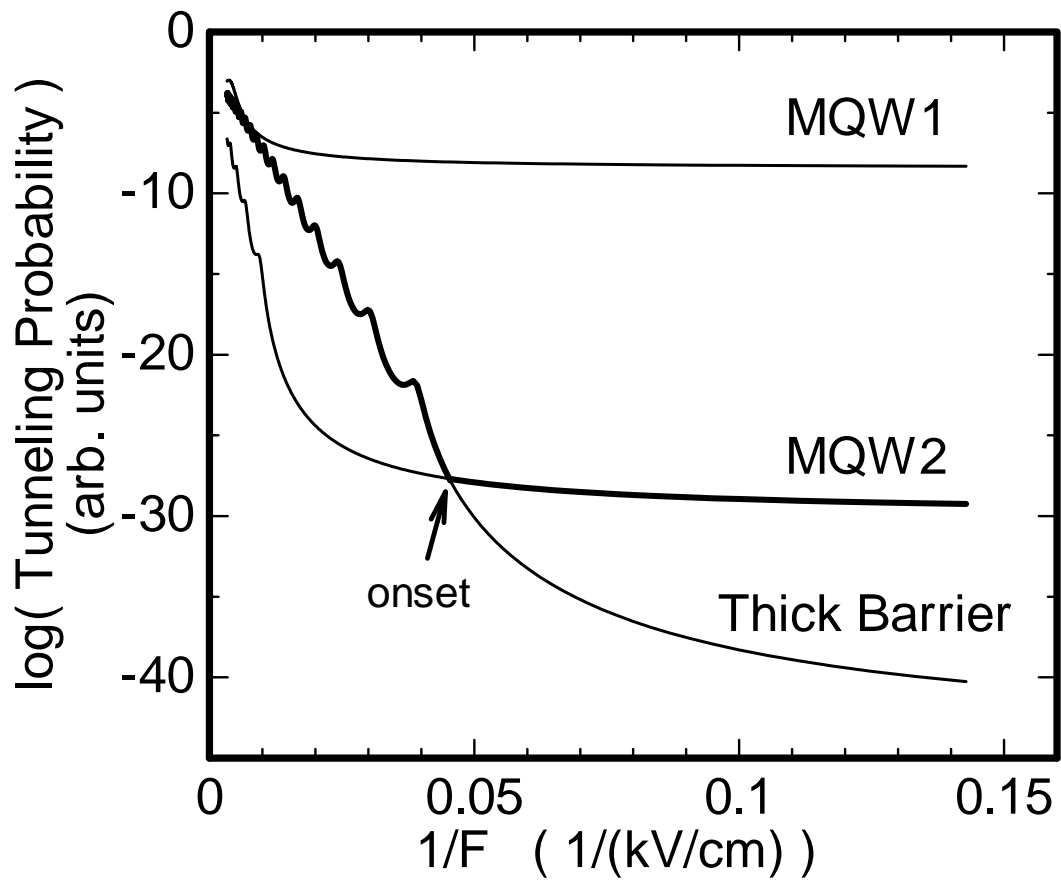


Fig. 4, K. Kawasaki et al., "Tunneling competition of..."